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学位論文題目	Impact of statistical reconstruction and compressed sensing algorithms on projection data elimination during medical X-ray computed tomography image reconstruction （X線ＣＴ画像再構成における投影データの削減に対する統計的再構成法および圧縮センシングアルゴリズムの影響）
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学位論文内容の要旨

CT (computed tomography) imaging technology has achieved shorter scanning times for each section and enabled simultaneous acquisition of multiple sections. Three-dimensional image processing and visualization techniques have been developed to support clinical demands. Greater use of CT technology, however, has resulted in delivering increased absorbed doses to patients. Statistical reconstruction methods used for CT image reconstruction have been applied clinically. Over the past decade, this development has brought new standards for reducing radiation exposure while achieving clinically acceptable image quality.

The sparse modeling theory permits fewer acquisition data to be used for complete reconstruction of signal, image, and audio processing. Compressed sensing is a solution for ill-posed inverse problems in image reconstruction, such as the sparse-view/under-sampling problem and noise removal from projection data. Total variation (TV) regularization is a key technology in determining the uniqueness of the solution.

The purposes of this study were to (1) examine the effect of statistical reconstruction algorithms and compressed sensing during TV regularization; (2) retain image quality despite projection data elimination; (3) explore the number and distribution of projection data needed to maintain adequate image quality; and (4) apply weighted TV values with prior image constraints.

Two CT images of the maxilla in a single series were used. Projection data acquisition was carried out. The projection data to be used for CT image reconstruction were adjusted by selective data removal. First, data intervals were increased from 1° to 2° or 4° and the number of projection data reduced from 360 to 180 and 90, respectively. Second, the sampling range was reduced from 0°–360° to 0°–180°. Third, the limited sampling range was combined with increased data intervals. Fourth, further projection data elimination was attempted using the TV regularization. For this step, the number of projection data were set at 45 and 36 in 0°–180° (at 4° and 5° intervals, respectively).

CT images were reconstructed following elimination of the projection data using the four methods. Whether the original image quality was maintained was evaluated in previous studies [Dong, J, et al. 2014, etc.]. It had been assumed that the use of 360 projection data collected in the range of 0°–360° at 1° intervals was sufficient to reproduce the original quality. We aimed to investigate the possibility of further projection data manipulation in combination

with statistical reconstruction algorithms. An algebraic reconstruction technique (ART) and the maximum likelihood-expectation maximization (ML-EM), an iterative restoration technique, were examined and compared with the traditional filtered back-projection (FPB), a standard inverse-Fourier transfer.

The compressed sensing theory proposed by Donoho, DL (2006) provided a theoretical and technical basis for CT image reconstruction under the condition of incomplete data acquisition. The theory suggested that, if the signal is sparse and the data are sampled at a lower rate than the Nyquist frequency, the original signal could be restored by appropriate optimization. Sidky, EY, et al. (2006) proposed the ART-TV technique based on TV regularization, which transforms the CT reconstruction issue to a constraint optimization problem.

When the sampling range was 0°–360°, image degradation by radial streak lines was apparent in the case of 4° intervals and 90 projections. But it is to a lesser extent on ART- and ML-EM-reconstructed images. When the range was 0°–180°, image degradation by radial streak lines was apparent, but the degradation was not as severe as the above case. The degradation on ART- and ML-EM-reconstructed images was less marked. When the ART-TV was applied for the combinations of 4° with 45 and 5° with 36 in 0°–180°, the image degradation was minimal despite the reduced projection data. When weighted TV values with prior image constraints were applied, images were reconstructed using sparse projection data without degradation.

The root-mean-square error and signal-to-noise ratio values both decreased with the reduced projection data, but the quality of the reconstructed images was best when using the ART-TV. Both ART and ML-EM required heavier calculation loading than FPB. Those for ART and ART-TV were compatible.

In conclusion, incomplete projection data due to either limited angle collection (from 360° to 180°) or thinning of the projection data (from 1° to 5° intervals) permit radiation dose reduction while sustaining image quality. It is achievable with the combination of statistical reconstruction algorithms and the compressed sensing method with TV regularization and prior image constraints. Despite heavier computational calculation loading, these methods should gain greater acceptance as computer calculation power continues to expand.

論文審査結果の要旨

近年，医療用X線CTに統計的画像再構成法が臨床応用されているが，計算負荷を増大させるが画質改善と患者の被ばく軽減を実現させた。スパースモデリングは，より少ないデータ取得で信号の完全な再構成を可能にする。そして圧縮センシングは不良設定問題を解決する方法である。

本論文は，X線CTに統計的画像再構成法と圧縮センシングを応用して，投影データを削減して画質を維持できるか検討した。全変動（TV, total variation）正則化をキー技術として，投影データ量を削減可能な処理法の開発を目的とした。提案された手法の特徴は以下のとおりである。

代数的再構成法（ART）と最大尤度期待値最大化法（ML-EM）とTV正則化を組み合わせて，投影データの大きな削減（最大で10分の1）の実現可能性を示した。また，従来のフィルタ補正逆投影法との明確な違いやARTと組み合わせたときのTV正則化の有効性も明らかにした。しかも，TV正則化は計算負荷の増大を示さなかった。先験的画像制約付きの加重TVを与えた場合も，スパースな投影データに対し劣化のない画像再構成ができた。

申請者は，X線CT画像の再構成において投影データを10分の1に減らせる可能性を示した。TV正則化は計算負荷も顕著に増加させないため，臨床応用可能な新知見を得たものであり，医用画像工学分野に対して貢献するところ大なるものがある。

よって，申請者は，北見工業大学博士（工学）の学位を授与される資格があるものと認める。